

## Review: Weak radiofrequency radiation exposure from mobile phone radiation on plants

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REVIEWS

## Review: Weak radiofrequency radiation exposure from mobile phone radiation on plants

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### ABSTRACT

**Aim:** The aim of this article was to explore the hypothesis that non-thermal, weak, radiofrequency electromagnetic fields (RF-EMF) have an effect on living plants. **Subject and methods:** In this study, we performed an analysis of the data extracted from the 45 peer-reviewed scientific publications (1996–2016) describing 169 experimental observations to detect the physiological and morphological changes in plants due to the non-thermal RF-EMF effects from mobile phone radiation. Twenty-nine different species of plants were considered in this work. **Results:** Our analysis demonstrates that the data from a substantial amount of the studies on RF-EMFs from mobile phones show physiological and/or morphological effects (89.9%,  $p < 0.001$ ). Additionally, our analysis of the results from these reported studies demonstrates that the maize, roselle, pea, fenugreek, duckweeds, tomato, onions and mungbean plants seem to be very sensitive to RF-EMFs. Our findings also suggest that plants seem to be more responsive to certain frequencies, especially the frequencies between (i) 800 and 1500 MHz ( $p < 0.0001$ ), (ii) 1500 and 2400 MHz ( $p < 0.0001$ ) and (iii) 3500 and 8000 MHz ( $p = 0.0161$ ). **Conclusion:** The available literature on the effect of RF-EMFs on plants to date observed the significant trend of radiofrequency radiation influence on plants. Hence, this study provides new evidence supporting our hypothesis. Nonetheless, this endorses the need for more experiments to observe the effects of RF-EMFs, especially for the longer exposure durations, using the whole organisms. The above observation agrees with our earlier study, in that it supported that it is not a well-grounded method to characterize biological effects without considering the exposure duration. Nevertheless, none of these findings can be directly associated with human; however, on the other hand, this cannot be excluded, as it can impact the human welfare and health, either directly or indirectly, due to their complexity and varied effects (calcium metabolism, stress proteins, etc.). This study should be useful as a reference for researchers conducting epidemiological studies and the long-term experiments, using whole organisms, to observe the effects of RF-EMFs.

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## Introduction

The number of mobile phones users was increased from about 2.2 to 5.9 billion between 2005 and -2011 (Key global telecom indicators, 2012). Approximately four mobile phone service providers exist in a given geographical area (Hyland, 2005). Consequently, the number of base stations was also increased to support the tremendous growth of mobile phone users (World Health Organisation, 2006). According to the International Telecommunication Union (ITU), this leads to high concentrations of radiofrequency electromagnetic fields (RF-EMFs) in the environment, besides high utilization of broadband technologies (International Telecommunication Union, 2012).

The World Health Organization (WHO) and International Agency for Research on Cancer (IARC) classified RF-EMFs from mobile phones as a “Possible

Human Carcinogen” (Group 2B) (World Health Organisation, 2011) (May 2011) based on scientific results presented in the literature. The Interphone study (INTERPHONE Study Group, 2010) (some evidence to suggest increased risk of glioma in heavy adult users  $> 1640$  hours) and the study by Hardell et al. (2006) indicate the growing risk of malignant brain tumors for users of cellular and cordless phones. The results from these studies have not been without controversy. The analysis presented in the another study by Swerdlow et al. (2011) proposes that there is no increase in risk, with accumulating evidence suggesting the fact that mobile phone use is safe for adults. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) report (International Commission on Non-Ionizing Radiation Protection, 1998) indicates that many of the experiments

show effects have not been independently replicated and when replication has been attempted the results could not be reproduced.

The recommendations of standard bodies ICNIRP (International Commission on Non-Ionizing Radiation Protection, 1998), IEEE (IEEE C95.1-2005, 2005) and European Committee for Electrotechnical Standardization (CENELEC) (CENELEC, 1995) for exposure limits are based on measurements of the short-term and the immediate health effects due to elevated tissue temperatures on the absorption of energy during exposure. The aims of these guidelines are to minimize heating effects. The specific energy absorption rate (SAR) is a measure of the energy absorption of the body when exposed to RF-EMFs. The European Union (EU) has specified the SAR limit of 2.0 W/kg while in the United States this is specified at 1.6 W/kg (International Commission on Non-Ionizing Radiation Protection, 1998). Besides these standard bodies, there are a group of members who have evaluated the published data from peer-reviewed scientific journals including European health risk assessment network (EHRAN) (European health risk assessment network, 2010) and Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) (SCENIHR, 2015) and performed the risk assessment due to RF-EMF exposure.

Biological effects of electromagnetic radiation from the mobile communication systems may depend on the mean power level, frequency and modulation of the electromagnetic signal. Various studies interrogated issues about the safety of extended use of mobile phones; however, most of these findings develop from epidemiological, animal (*in vivo*) and cell (*in vitro*) studies. A few studies investigated effects of RF-EMF radiation on plants. In recent decades, a few researchers have reviewed RF-EMF effects on plants (Belyavskaya, 2004; Cucurachi et al., 2016; Panagopoulos et al., 2016; Senavirathna and Takashi, 2014; Vian et al., 2016) and observed the potential trend of RF-EMF influence on plants. On the other hand, phenotypic plasticity of plants will allow them to change their structure and function; hence, plants adapt to environmental changes (Nicotra et al., 2010). Plants are naturally affected by environmental stresses due to their immobility. The relationship between environmental stress and plant development is one of the important research fields dedicated by biologists and physicists (Xiujuan et al., 2003). Plants could respond to the environmental factors of wind, rain, electric field and ultraviolet radiation and adjust its physiological condition to adapt to the change of environment (Braam and Davis, 1990; Braam et al., 1996; Mary and Braam, 1997).

Apart from these opinions, there is still a lack of grounds for the observed biological effects of weak RF-EMF on plants. In the light of this ambiguity, in this article, we perform an analysis of data from the 45 peer-reviewed scientific journals (1996–2016) with 169 experimental observations carried out in the scientific literature that discussed the potential effects on plants exposed to the non-thermal weak RF-EMF exposure from the mobile phone radiation.

## Material and methods

The investigated frequencies of operation and the modulation signal used by the global system for mobile communications (GSM), continuous wave (CW), pulsed wave (PW) or pulsed electromagnetic fields (PEMF), time division multiple access (TDMA), code division multiple access (CDMA), frequency division multiple access (FDMA), Gaussian minimum shift keying (GMSK), GSM basic, GSM discontinuous transmission (GSM DTX), GSM talk, GSM non-discontinuous transmission (GSM non-DTX), international mobile telecommunication-2000 (IMT-2000), wideband CDMA (WCDMA), enhanced data rate for GSM evolution signal (EDGE) and universal mobile telecommunication system (UMTS) systems were used in this analysis (Table 1).

Our analysis interrogated published experiments that considered the non-thermal RF-EMF on 29 different plants including broad bean, ligneous, soybean, maize, brassicaceae, roselle, pea, fenugreek, parrot feather, duckweeds, tomato, red bean, hyacinth bean, mologabean, parsley, dill, celery, onions, rice plant, mung bean, lentil, common wheat, aspen, alfalfa, Plectranthus, woad, flax, spruce and beech to observe the effects. In this study, physiological or morphological effects of plants or plant response (changed or unchanged) due to exposure to weak radiofrequency radiation from a mobile phone is defined as the changes in (i) plant growth rate, (ii) seed germination rate (primary shoot and root length), (iii) thermographic imaging, (iv) carbohydrate metabolism, (v) oxidative damage/stress, (vi) gene expression, (vii) DNA damage, (viii) reactive oxygen species (ROS), (ix) cell function, enzyme activities, (x) mitotic index and mitotic abnormalities, (xi) mutation rates and genomic stability, (xii) pigmentation (chlorophyll concentration) and (xiii) chromosomal aberrations and micronuclei.

## Collection of raw data

This analysis was made to pool the data of the reported experimental observations (169 experiments) from the

**Table 1.** Frequency used by different mobile phone networks.

Generation	Frequency	Technology	Features
1G	800 MHz (824–849 MHz, 869–894 MHz)	FDMA	Based on analog system, 1G uses channel bandwidth of 30 kHz, data transmission up to 2.4 Kbps
2G	900 MHz (890–915 MHz), 1800 MHz (1850 –1910 MHz), 1930–1990 MHz	TDMA, CDMA	2G (GSM), GSM (each channel is split into eight 0.577us bursts), 2G uses channel bandwidth of 200 kHz for voice transmission. 2G allows multiple users on a single channel through multiplexing data with voice, data transmission up to 14–64 Kbps
2.5G	800 MHz	CDMA	Enhanced 2G, higher data rates, GPRS, EDGE, data transmission up to 64 Kbps
3G	850, 900, 1700, 1900 (1920–1980 MHz), 2100 MHz (2110–2170 MHz)	CDMA2000 (1×RTT, EVDO), UMTS (WCDMA), TD-SCDMA	High-speed digital cellphones, 3G is based on WCDMA (wideband code division multiple access) technology, UMTS, 3G uses channel bandwidth of 1.25 MHz for voice transmission for 1×RTT and increases data rate using 3.75 MHz for 3×RTT, TD-SCDMA uses 1.6 MHz bandwidth. Provides high internet browsing speed, video streaming, video calling, data transmission 125 kbps to 2 Mbps
3.5G	850 MHz	HSPA	Next-GO—"Broadband" cellphones, 3G on steroids (3.5G), it introduces a high-speed downloading channel called HS-DSCH, rated up to 42 Mbps, evolved HSPA (HSPA+), dual carrier technology and 64QAM modulation
4G	700 MHz, 850 MHz, 900 MHz, 1800 MHz, 1805–1820 MHz (transmit) and 1710–1725 MHz (receive), 1900 MHz, 2100 MHz, 2300 MHz, 2500 MHz, 2600 MHz, 3500 MHz	WiMax, LTE	Enhanced 3G, high-speed and IP-based networks, supports HD streaming, HD phones, data transmission up to 400 Mbps
5G	6–100 GHz	CDMA	mmWave frequency (next major phase of mobile phone communication will come to market in 2018), 4G + <a href="http://WWW">WWW</a> , IP-based networks (internet of things), data transmission up to 1000 Mbps (gigabit speed)

45 peer-reviewed scientific studies. Twenty-nine different plant types have been used for the published studies to examine the effect of weak radiofrequency radiation from mobile phones. The raw data presented in Tables 2–5 specify the variables and experimental protocols including exposure conditions.

### Data inclusion criteria

In our analysis, we considered experiments from the reported studies for exposure conditions in the frequency ranging from 895 to 3500 MHz. Although current mobile phone communication providers use the frequencies from 895 to 3500 MHz, we included a few studies that used high frequencies, as prototypes of fourth-generation (4G) and fifth-generation (5G) mobile phone communication lines are currently being underdeveloped using very high frequencies. Selected 4G networks are utilizing 3.5 and 5.5 GHz frequencies (Lai and Wong, 2008).

SAR is used to observe how RF-EMF exposure could cause heating of biological matter. Hence, for our analysis, we included the studies that used SAR for their experiments on plants. In our analysis, we included experiments that reported results when (i) SAR values are less than 50 W/kg, (ii) power flux densities are less than 50 W/m<sup>2</sup> and (iii) electric field strengths are less than 100 V/m. We included the reported studies that used all exposure durations to observe the effects of the

short-term exposures as well as of the long-term exposures. Nonetheless, in our analysis, we excluded experiments that reported results when (i) no complete dosimetry is disclosed or (ii) if the publication is not published in peer-reviewed scientific journals.

### Analysis of raw data

The raw data presented in Tables 2–5 specify the variables that were in the non-thermal RF-EMF exposure conditions and experimental protocols used in this study. Experimental protocols used by different laboratories have considered a few variables including carrier frequency, SAR, modulation method and exposure time. However, no analysis was directly differentiated frequency, exposure duration and publication year to acquire the potential trend of experiments due to the RF exposure for their analysis.

We pooled and analyzed the reported studies based on the impact of variables that they used for their studies. The descriptive details of the study based on the publication year were analyzed to observe the impact of the technology from 1996 to 2016. Then the comparison of the exposure durations was investigated to detect the trend of the effect. Different exposure duration was observed by further analyzing it in smaller groups, separately: (i) entire exposure time, (ii) 0 < hour ≤ 2, (iii) 2 < hour ≤ 24, (iv) 1 < day ≤ 7, (v) 1 < week ≤ 13 and (vi) 0.25 < year ≤ 6.

**Table 2.** Weak RF-EMF exposure from mobile phones on plants: exposure conditions used in published experiments.

No.	Exposed plant (scientific name)	Exposure system	Analysis	Results	Response	authors
1	Broad bean seedlings ( <i>Vicia faba</i> L.)	915 MHz (CW), SAR 0.4, 1.6 W/kg, power flux density: 23, 35.2, 46 W/m <sup>2</sup> , power 15, 23, 3 W for 72 hours using TEM cell	Genotoxic effects: micronuclei in secondary root tips	The micronucleus frequency was significantly increased in all exposure groups compared to the control group. Hence, the article concludes that exposure of broad bean seedlings ( <i>Vicia faba</i> ) to EMF could have genotoxic effects.	Changed	Gustavino et al. (2016)
2	Whole small lignous plants ( <i>Rosa hybrida</i> )	900 MHz (GSM), SAR 0.00072, 1.15 W/kg, electric field strength 5, 200 V/m for 30 minutes in three times using a mode stirred reverberation chamber (MSRC) acting as a Faraday cage	Shoot length	Delayed and significant reduced growth were observed in post-formed secondary buds. Hence, the article concludes that exposure to EMF only affected increment of post-formed organs.	Changed	Gremiaux et al. (2016)
3	Soybean plants seedlings ( <i>Glycine max</i> )	900 MHz (GSM – CW, PW), SAR 0.48 μW/kg, 0.049, 0.39, 2.6, 20 mW/kg, power flux density: 0.1, 11, 86, 560, 4400 mW/m <sup>2</sup> , electric field strength: 0.56, 5.7, 41 V/m continuous for 2 hours and continuous for 5 days using GTEM cell	Growth of soybean seedlings (growth of seedlings 1 week (or in Experiment 5 two days) after exposure: length of epicotyl (i.e. between leaves and cotyledon), length of hypocotyl (i.e. between cotyledon and start of roots), length of roots)	Seedlings exposed to GSM signals with an electric field strength of 41 V/m appeared significantly shorter epicotyls. No significant changes were observed when exposed to electric field strength of 5.7 V/m. However, exposure of seedlings to a weak electric field strength for 5 days resulted in significantly shorter epicotyls and hypocotyls and in significantly elongated roots. The roots of seedlings that were exposed to CW with an electric field strength of 41 V/m were significantly shorter, while in the group exposed to CW with an electric field strength of 5.7 V/m, significantly shorter hypocotyls were observed.	Changed	Halgamuge et al. (2015)
4	Maize seedlings ( <i>Zea mays</i> L.)	1800 MHz (CW), SAR 1.69 W/kg, power flux density 332 mW/m <sup>2</sup> , power 0.1 W, continuous for 30 minutes, 1, 2 and 4 hours using antenna, chamber, 5 petri dishes with 10 seedlings each	Effects on plants: growth and carbohydrate metabolism (roots, coleoptiles, tissue homogenates and extracts)	(i) The length of roots and coleoptiles as well as the chlorophyll concentration was significantly reduced. (ii) The carbohydrate and reducing sugar contents were significantly increased after 1 hour of exposure. (iii) The enzyme activities and invertase were significantly increased, whereas the enzyme activity of the starch phosphorylates was significantly decreased at the same time. No distinct drift was observed in the enzyme activities of the phosphatases. In all parameters, a susceptibility toward greater effects with increasing exposure duration was observed.	Changed	Kumar et al. (2015)
5	Brassicaceae ( <i>Lepidium sativum</i> )	900, 1800 MHz, field intensity 70–100 μW/m <sup>2</sup> for 10 days	Plant germination	Plant germination did not occur under 70–100 μW/m <sup>2</sup>	Changed	Cammaerts et al. (2015)
6	Maize ( <i>Zea mays</i> )	1000 MHz, SAR 0.47 W/kg for 1–8 hours using TEM cell	Growth rate	Reduced growth was observed of plants (about 50% after 8 hours of exposure)	Changed	Racuciu et al. (2015)
7	Roselle plants ( <i>Hibiscus sabdariffa</i> )	900 MHz (GSM), field strength 0.8–1.12 V/m for 30 days	Flower bud abscission	Observed the reduction of flower bud production and abscission with the increased distances from the GSM mast	Changed	Oluwajobi et al. (2015)
8	Pea ( <i>Pisum sativum</i> ), Fenugreek ( <i>Trigonella foenumgraecum</i> )	900, 1800 MHz, for 0.5, 1, 2, 4, 8 hours	Germination percentage, seedling length, proteins, lipid and guaiacol content	RF exposure from mobile phone affected with both the biochemical and morphological processes and affected the growth and nodule formation in the plants	Changed	Sharma et al. (2014)

(Continued)

**Table 2.** (Continued).

No.	Exposed plant (scientific name)	Exposure system	Analysis	Results	Response	authors
9	Parrot feather ( <i>Myriophyllum</i> <i>aquaticum</i> Verdc.) plants	2000 MHz (CW), power flux density: 0.65–1.42 W/m <sup>2</sup> , 15.6 V/m for 60 minutes using exposure chamber	Thermographic imaging; nanometric elongation rate fluctuation (NERF) using a statistical interferometry technique	Nanometer-scale elongation rate fluctuations in the plant stem were altered and statistically significant reduction was observed.	Changed	Senaviratha et al. (2014a)
10	Duckweeds ( <i>Lemna minor</i> )	2000, 2500, 3500, 5500, 8000 MHz (CW), power field intensity 5.3, 6.6, 6.5, 6.5, 5.4 W/m <sup>2</sup> , electric field strength 45, 50, 55, 60 V/m for 0.5, 1 and 24 hours using anechoic chambers	Infrared thermographic images; Non-photochemical quenching in dark adaptation (NPQ D), non-photochemical quenching in steady-state light (NPQ S)	(i) 2 GHz exposure: the NPQ S value increased in all exposures. Moreover, the NPQ D reduced by after 30 minutes and 24-hour exposures, whereas it increased after a 1-hour exposure period. (ii) 2.5 GHz EMR exposure: the NPQ S reduced in the 30-minute, 1-hour and 24-hour exposure durations. (iii) NPQ D reduced after 30 minutes of exposure, increased after a 24-hour and 1-hour exposure durations. (iv) temperature was not changed to prove that the effect is non-thermal.	Changed	Senaviratha et al. (2014b)
11	Parrot feather ( <i>Myriophyllum</i> <i>aquaticum</i> Verdc.) plants	2000, 2500, 3500, 5500 MHz (CW), electric field strength 23, 25, 30 V/m for 60 minutes using anechoic chambers	Changes in the electric potential (EP) inside plants	Changes in the electric potential were observed (statistically significant) with 2000, 5500 MHz frequencies. The temperature of the plants was not altered due to the EMR exposure. Therefore, this study indicates the support of the EMR effect on the electric potential in plants.	Changed	Senaviratha and Asaeda (2014)
12	Tomato ( <i>Solanum</i> <i>Lycopersicum</i> <i>esculentum</i> Mill)	1250 MHz, electric field strength 6 V/m for 10 days using patch antenna	Growth rate and cell accumulation	Observed the influence of the growth and the differentiation and evoke an increase of protein accumulation in the cell	Changed	Rammal et al. (2014)

**Table 3.** Weak RF-EMF exposure from mobile phones on plants: exposure conditions used in published experiments.

No.	Exposed plant (scientific name)	Exposure system	Analysis	Results	Response	authors
13	(i) Mung bean ( <i>Vigna</i> , <i>Fabaceae</i> ), (ii) Red bean ( <i>Vigna</i> , <i>Fabaceae</i> ), (iii) Soybeans ( <i>Glycine</i> , <i>Fabaceae</i> ), (iv) Hyacinth bean ( <i>Loblab</i> , <i>Fabaceae</i> ) and (v) Mologa bean ( <i>Vigna</i> , <i>Papilionaceae</i> )	1800 0.48–1.45 mW/cm <sup>2</sup> , SAR 1.0–7.1 mW/kg for 4, 24 hours	Plant growth	Reduction of height and fresh weight were observed	Changed	Chem and Chen (2014)
14	(i) Parsley ( <i>Petroselinum crispum</i> ), (ii) Dill ( <i>Anethum graveolens</i> ), (iii) Celery ( <i>Apium graveolens</i> )	860–910 MHz (GSM), power flux density 100 mW/m <sup>2</sup> for continuous exposure for 3 weeks using the anechoic chamber	Effects on plants: (i) leaf anatomy, (ii) etheric oil content and (iii) volatile emissions	Microwave irradiation established a stress to the plants, (i) rising in larger emissions of green leaf volatiles, (ii) upregulation of terpenoid emissions and (iii) modification in essential oil content and foliage anatomy. The authors conclude that exposure of different aromatic plants to an electromagnetic field of 2.4 GHz or 900 MHz (WiFi or GSM) could influence leaf anatomy as well as the etheric oil content and volatile emissions, which might be an indication for stress.	Changed	Sorani et al. (2014)
15	Onions ( <i>Allium cepa – bulbs</i> )	890–915 MHz (GSM, PW), SAR 1.4 W/kg, power density 4.79 μW/m <sup>2</sup> , 0.0005 W/m <sup>2</sup> for continuous for 3 hours/day on 3 days, for 1 hour/day on 3 days	(i) Mitotic index and mitotic abnormalities (ii) Chromosomal aberrations and micronuclei	GSM 900 mobile phone radiation increased the (i) mitotic index, (ii) the frequency of mitotic and (iii) chromosome abnormalities and (iv) the micronucleus frequency in a time-dependent manner.	Changed	Pesnya and Romanovsky (2013)
16	MR 219 rice variety ( <i>Oryza sativa</i> L.)	2450 MHz (2280–2490 MHz) (CW), energy power 1.58 mW for 1, 4, 7, 10 hours using exposure chamber with dipole antenna	Seed germination rate (primary shoot and root length), germination percentage and mean germination time	The most successful influences of microwave frequencies on the seed germination, shoot and root growth showed after 10 hours of exposure time in the period of 5 days while other exposure times showed the moderate effects on germination.	Changed	Talei et al. (2013)
17	Tomato ( <i>Lycopersicon esculentum</i> Mill.)	900 MHz (PW), 970 μW/m <sup>2</sup> , 0.6 V/m for 6 years	Growth rate/burn leaves of trees	Trees damaged due to mobile phone base stations	Changed	Walddmann-Selsam and Eger (2013)
18	Mung bean ( <i>Vigna radiata</i> )/Wilczek, hypocotyls	900 MHz (GSM, PW—talk and listen mode), power flux density: 8.54 μW/cm <sup>2</sup> , electric field strength 5.7 V/m continuous for 0.5, 1, 2 hours using chamber with 2 mm thick aluminum sheets shielded	Effects on plants: root growth and oxidative stress	The average root length and the number of roots per hypocotyl were reduced and the inhibitory effect increased with the increased exposure duration. The exposure enhanced the enzyme activities of proteases, polyphenol oxidases and peroxidases in plants and hypocotyls.	Changed	Singh et al. (2012)
19	Lentil, Medic seeds ( <i>Lens culinaris</i> )	1800 MHz (GSM), power 1 mW, SAR 0.76 W/kg for 48 hours	Plant germination, root growth and mitotic division of root tips Protein metabolism: protein and antioxidant enzymes	Reduction of seedlings root growth (60%) and mitotic index (12%). Abnormal mitosis increased (52%)	Changed	Akbal et al. (2012a)
20	Mung bean ( <i>Vigna radiata</i> ), Common wheat ( <i>Landoltia punctata</i> ( <i>Triticum aestivum</i> ))	900 MHz for 72 hours		Plant growth reduction was observed in <i>Vigna</i> (21%) and <i>Triticum</i> (50%) and showed the inhibitory effect on various morphological parameters, with altered biochemical response. Reasons for this reduction are correlated with reduction in protein synthesis and improved membrane damage and antioxidant enzyme activity.	Changed	Akbal et al. (2012b)
21	Duckweed <i>Landoltia punctata</i> ( <i>Spirodela oligorrhiza</i> )	1287 MHz, electric field strength 1.8, 7.8 V/m for 24 hours from a transmitting antenna	Biological cell stress	Alanine accumulation was suppressed due to the exposure from RF irradiating antennas	Changed	Monseise et al. (2011)

(Continued)

**Table 3.** (Continued).

No.	Exposed plant (scientific name)	Exposure system	Analysis	Results	Response	authors
22	Mung bean ( <i>Vigna radiata</i> ) Wilczek cv. ML-5	900 MHz (GSM), power flux density 8.55 $\mu\text{W}/\text{cm}^2$ continuous for 0.5, 1, 2, 4 hours using shielded chamber acting as Faraday cage	Effects on plants: germination and growth	Following key points were observed (i) germination of plants depends on the exposure time, (ii) 4-hour exposure reduced the germination by half, (iii) reduced the length of the seedlings and dry weight of bean after exposure for 0.5, 1, 2 and 4 hours, (iv) the contents of proteins and carbohydrates were decreased.	Changed	Sharma et al. (2010)
23	Peas ( <i>Pisum sativum</i> L.)	947.5 MHz (GSM, PW, CW) power flux density 4.8 W/ $\text{m}^2$ , electric field strength 42.6 V/m for 1, 12, 14 hours	Change in chlorophyll fluorescence concentration	Exceptional change during the day, pattern of chlorophyll fluorescence parameters was observed. (i) Longer exposure to continuous GSM 900 EMF simulating radiation from base station in rush hour for 14 days, (ii) 1 hour/day, (iii) 12 hours did not stimulate stress in pea plants determined by the prompt chlorophyll fluorescence parameters.	Changed	Kouzmanova et al. (2010)
24	Aspen seedlings ( <i>Populus</i> )	1000–3000 MHz, field intensity 117dBm to 87dBm, power 1.99e-15 to 1.99e-12 W for 8 weeks using Faraday cage	Growth rate	Growth rate reduced in aspen seedlings due to ambient EMR.	Changed	Haggerty (2010)

**Table 4.** Weak RF-EMF exposure from mobile phones on plants: exposure conditions used in published experiments.

No.	Exposed plant (scientific name)	Exposure system	Analysis	Results	Response	authors
25	Plectranthus ( <i>Lamiaceae</i> )	902 MHz (GSM, PW), power flux density 4.8 W/m <sup>2</sup> , power 2W, for 60 minutes in chamber	Alterations in enzyme activities in Plectranthus plant leaves after exposure	After the exposure, activities of the three examined enzymes were reduced, though, they increased after 24 hours	Changed	Kouzmanova et al. (2009)
26	Mung bean ( <i>Vigna radiata</i> )	900 MHz (GSM, PW), power flux density: 8.55 $\mu$ W/cm <sup>2</sup> , electric field strength 5.7 V/m continuous for 0.5, 1, 2, 4 hours using shielded chamber acting as Faraday cage	Effects on plants: root growth and oxidative stress	RF-EMF exposure (i) significantly decreases root growth of mung bean by inducing ROS-generated oxidative stress regardless of increased activities of antioxidant enzymes, (ii) significant upregulation in the activities of enzyme searching enzymes in the roots and (iii) increased oxidative stress and cellular damage.	Changed	Sharma et al. (2009a)
27	Mung bean ( <i>Phaseolus aureus</i> )	900 MHz (GSM), for 1, 2, 4 hours	Radicle and plumule growth	Reduced the radicle and plumule growth and decreased the protein and carbohydrate amount in radicles through interference with associated biochemical changes.	Changed	Sharma et al. (2009b)
28	Common wheat ( <i>Triticum aestivum</i> )	2450 MHz, 126 mW/mm <sup>2</sup> for 5–25 seconds	Oxidative metabolism	Reduced the oxidative response of plants to high salt treatment	Changed	Chen et al. (2009)
29	Onion ( <i>Allium cepa L.</i> )	900 MHz (GSM), power density 0.3, 1.4, 4.2 and 38.2 W/m <sup>2</sup> , field strengths of 10, 23, 41 and 120 V/m for 2, 4 hours using GTEM cell	Cytogenic and genotoxic effects in plants and growth of plants	(i) increase in the mitotic index in root tips was observed and (ii) mitotic and chromosomal abnormalities were found; nevertheless, root length and germination rates did not alter considerably.	Changed	Tkalec et al. (2009)
30	Common wheat ( <i>Triticum aestivum</i> )	902 MHz (GSM), power flux density 3.9 W/m <sup>2</sup> for 60 minutes	Hydrogen peroxide ( $H_2O_2$ ) concentration, oxidative stress, reactive oxygen species, level	Results show that one-hour exposure to 900 MHz EMF did not stimulate oxidative stress in Common wheat at investigated parameters.	Unchanged	Dragolova et al. (2009)
31	Maize ( <i>Zea mays L.</i> )	935.2–960.2 MHz (GSM), power flux density 0.7–1.5 W/m <sup>2</sup> for 2-week continuous from base station	Germination rates	Observed the increased germination rates of seed and pigmentation (chlorophyll) and seedling growth rates. Germination rate was found to be maximum at 1.5 W/m <sup>2</sup> and the chlorophyll concentration was highest at 0.7 W/m <sup>2</sup> .	Changed	Khalfallah and Sallam (2009)
32	Brassicaceae ( <i>Arabidopsis thaliana</i> ) – plant cell suspension cultures	1900 MHz (CW), SAR 0.75 W/kg, power flux density: 8 mW/cm <sup>2</sup> , electric field strength: 174 V/m, continuous for 24 hr using dipole antenna, flask placed inside a Faraday cage	Gene expression, RT-PCR	With RF exposure, stress-related transcripts and cellular energy state	Unchanged	Engelmann et al. (2008)
33	Tomato ( <i>Lycopersicon esculentum Mill.</i> ) / VFN8	900 MHz, power flux density 0.066 W/m <sup>2</sup> , electric field strength 5 V/m for 10 minutes using a mode stirred reverberation chamber (MSRC)	Accumulation of stress-related transcripts and cellular energy	In addition to the stress-related mRNA accumulation and its dependency on the second messenger calcium, this article spotted a strong correlation between total and polysomal transcript abundance, ATP concentration and adenylate energy charge.	Changed	Roux et al. (2008b)
34	Tomato ( <i>Lycopersicon esculentum VFN8</i> )	900 MHz (CW), power flux density 0.066 W/m <sup>2</sup> , field strength 5 V/m for 10 minutes using a mode stirred reverberation chamber (MSRC)	Molecular biosynthesis (accumulation of stress-related transcripts and cellular energy state)	Results show that tomato plants comprise great models to study the impact of HF-EMF on life, as they respond to EMF.	Changed	Roux et al. (2008a)
35	Tomato plants ( <i>Solanum Lycopersicon esculentum</i> , VFN-8)	900 MHz (CW), power flux density 0.066 W/m <sup>2</sup> , field amplitude of 5 V/m for 10 minutes using a mode stirred reverberation chamber (MSRC) chamber act as a Faraday cage	mRNA accumulation, RT-quantitative PCR analysis	Some exposure durations stimulated seed germinations and seedling growth. Furthermore, the RNA and DNA of seedlings developed from exposed seeds were tremendously increased for short exposure durations.	Changed	Beaubois et al. (2007)
36	Maize ( <i>Zea mays L.</i> )	900 MHz (GSM), SAR 0.95 mW/kg, power density 0.05 W/m <sup>2</sup> for 0.5, 1, 2, 4, 8, 12, 24, 36 hours Using TEM cell	Germinations and seedling growth, assimilatory pigments and average nucleic acid	(Continued)	Racuciu and Miclaus (2007)	

**Table 4.** (Continued).

No.	Exposed plant (scientific name)	Exposure system	Analysis	Results	Response	authors
37	Duckweed ( <i>Lemna minor</i> L.)	900 MHz (CW) power flux density 0.3, 1.4, 4.2, 38.2 W/m <sup>2</sup> , electric field strength 10, 23, 41, 120 V/m continuous for 2, 4 hours using GTEM cell HSP70 expression using Western blot	Oxidative stress (lipid peroxidation, hydrogen peroxide content, enzyme activities, isoenzyme pattern of antioxidative enzymes, HSP70 expression using Western blot)	Non-thermal exposure to investigated RF fields stimulated oxidative stress in duckweed, in all exposure actions the below were observed: (i) no changes in isoenzyme patterns of antioxidative enzymes or HSP70 level (ii) ascorbate peroxidase activity was significantly decreased after exposure at 10 V/m and 23 V/m (iii) increased pyrogallol and catalase enzyme activity at 120 V/m (iv) the effects depended on the EMFs frequencies applied, field strength, modulation and exposure time.	Changed	Tkalec et al. (2007)

**Table 5.** Weak RF-EMF exposure from mobile phones on plants; exposure conditions used in published experiments.

No.	Exposed plant (scientific name)	Exposure system	Analysis	Results	Response	authors
38	Tomato ( <i>Lycopersicon esculentum</i> Mill.) / VFN8	900 MHz (CW), power flux density 0.066 W/m <sup>2</sup> , field strength 5 V/m for 10 minutes using a mode stirred reverberation chamber (MSRC) reverberation chamber	Molecular biosynthesis (accumulation of stress-related transcripts (total transcripts for net accumulation and polyribosome-associated transcripts for current translation) and cellular energy state)	New evidence to support the hypothesis that plants perceive and respond to microwave exposure as though it was an injurious treatment. Authors noticed a strong correlation between all the parameters measured (ATP concentration, total and polysomal transcript abundance and adenylate energy charge).	Changed	Roux et al. (2007)
39	Tomato ( <i>Solanum lycopersicum</i> Mill/ <i>esculentum</i> Mill.)/ VFN8	900 MHz (UMTS, CDMA), power flux density 0.06 mW/cm <sup>2</sup> , electric field strength 3.9 V/m, for 10 minutes using MSRC (mode stirred reverberation chamber)	Stress response of tomato, mRNA (quantitative RT-PCR)	Results showed that (i) low amplitude, short duration, 900 MHz EMF evoked the accumulation of the stress-related transcript (mRNA) (ii) this accumulation was rapid—peaking 5–15 minutes after exposure, strong—3.5-fold and was alike to that evoked by injurious stimuli.	Changed	Vian et al. (2006)
40	Tomato ( <i>Solanum lycopersicum</i> Mill/ <i>esculentum</i> Mill.)/ VFN8	900 MHz (GSM, CW), power flux density 0.066 W/m <sup>2</sup> , electric field strength 5 V/m, for 2, 10 minutes, using MSRC (mode stirred reverberation chamber)	Stress response of tomato, quantitative RT-PCR	Exposure to the RF-EMFs: (i) the kinetics and amplitudes of the transcripts exhibited obvious similarities with physiologic responses and injurious treatments. (ii) induced a biphasic response—the levels of all three transcripts increased	Changed	Roux et al. (2006)
41	Alfalfa ( <i>Medicago sativa</i> )	2400, 5850 MHz, densities of 5, 12 W/m <sup>2</sup> for 7 weeks	Alternation in morphology, chlorophyll concentrations, stem lengths	No alteration was observed in morphology, chlorophyll concentrations, stem lengths or the dry or wet weight.	Unchanged	Skiles (2006)
42	Seedlings of Woad ( <i>Isatis indigotica</i> )	2450 MHz, power flux density 1.26 mW/mm <sup>2</sup> for 8 seconds	Cell function (i) enzyme activities of alpha-amylase, (ii) alanine transaminase, (iii) glutamic oxaloacetic transaminase	RF-EMFs were considerably improved: (i) The enzyme activities of amylase, transaminase and proteinase of the cotyledon pre-treated, (ii) The bio-photon emission was greater from seedlings than from the seeds.	Changed	Chen et al. (2005)
43	Duckweed ( <i>Lemna minor</i> L.)	900, 1900 MHz (CW, AM), power flux density 0.26, 1.4, 4.45 W/m <sup>2</sup> , electric field strength 10, 23, 41 V/m for 2, 4 and 14 hours using GTEM cell	Plant growth	Plant growth exposed to the 23 V/m electric fields of 900 MHz for 2, 4 hours considerably decreased in comparison with the control. A modulated field at 900 MHz inhibited the plant growth. Irradiation of plants to lower field strength (10 V/m) for 14 hours affected significant decrease at 1900 MHz, while 900 MHz did not influence the growth.	Changed	Thalec et al. (2005)
44	Flax seedlings ( <i>Linum usitatissimum</i> L. var Ariane)	900 MHz (GSM, PW), 1 mW/cm <sup>2</sup> , power 2W for 2 hours using cellular phone	Effects on plants, number of meristems	The significant changes were observed in ion distribution for magnesium, calcium, potassium, and sodium due to the RF-EMF.	Changed	Tafforeau et al. (2002)
45	Spruce ( <i>Picea abies</i> (L.) Karst) and Beech ( <i>Fagus sylvatica</i> L.)	2450 MHz, power densities of 0.007–300 W/m <sup>2</sup> (Group 1: 0.1–0.3 mW/cm <sup>2</sup> , Group 2: 1–3 mW/cm <sup>2</sup> , Group 3: 10–30 mW/cm <sup>2</sup> , Group 4: < 0.001 mW/cm <sup>2</sup> ) for 3.5 years	Growth rate and photosynthetic activity	In both plants, the foliar concentrations of calcium and sulphur decreased with an increased RF-EMF through the second year; however, the observation was not presented in the third year.	Unchanged	Schmutz et al. (1996)

The 3G/UMTS uses 1885–2025 MHz and 2110–2200 MHz, on a worldwide basis, while GSM uses 900 and 1800 MHz. In UMTS, both the carrier frequency and the modulation method differ significantly from GSM, and thus different biological responses can be expected. As carrier frequency and modulation formats differ significantly across wireless standards, it is possible that different biological responses may be expected or observed. To incorporate this, we pool the experiment data, based on used frequencies and exposure durations. Our analysis considered the effect of several subgroups of frequency ( $f$ ): (i) all frequencies, (ii)  $800 \leq f \leq 1500$  MHz, (iii)  $1500 < f \leq 2400$  MHz, (iv)  $2400 < f \leq 2500$  MHz, (v)  $2500 < f \leq 3500$  MHz and (vi)  $3500 < f \leq 8000$  MHz values.

Although there were Wi-Fi and other technologies that use 2.45 GHz frequencies, we did not consider this, as it is apart from the scope and aim of this analysis to observe the effect of such technologies.

### **Statistical analysis**

We perform statistical analysis to organize the data and predict the trends based on the analysis. To complete this, we tested whether the probability of an effect (changed) being reported in the literature was statistically different to no effect (unchanged) being reported. In statistics, the binomial distribution is the base for the common binomial test of statistical significance. This method is used to observe the importance of the “success–failure” experiments (in our case physiological or morphological effects on plants: “changed–unchanged”). Therefore, in this article, we used this knowledge to obtain the statistical significance of the analysis. The null hypothesis in our analysis is that the probability of an experiment showing effects or no effects (physiological or morphological effects on plants: changed or unchanged) is equal. The alternative hypothesis is that these probabilities are statistically different. To test for significance, a binomial probability density function was used,

$$p(k) = \binom{n}{k} p^k (1-p)^{n-k},$$

where  $p(k)$  is the probability of having  $k$  positive experiments (physiological or morphological effects on plants: changed) from the  $n$  reported experiments,  $p$  is equal to 0.5, and the null hypothesis is rejected if  $p(k) < 0.05$ , as used in (Halgamuge and Skafidas, 2016). The MATLAB (MathWorks Inc., Natick, MA, USA) R2014b has been used to carry out analysis on a computer with an Intel Core Intel Core i7 CPU.

### **Results**

The aim of this work was to investigate the hypothesis that non-thermal, weak, RF-EMFs have an effect on living organisms, in our case, on plants. Our analysis of the reported results demonstrates that RF-EMFs might impact on plants. In spite of that, it suggests a possible benefit of drawing attention to the significance of the exposure limits to weak RF-EMFs.

In our final analysis, we pooled the data, showing a statistically significant difference in various parameters (published year, exposure time, frequency and plant type) for different plants. This analysis showed a statistically significant difference in 29 different species plants from other species in Tables 2–5. Some of the important parameters considered for this analysis are: (i) name of the plant (including the scientific name), (ii) exposure system (SAR (W/kg), power flux density (W/m<sup>2</sup>), electric field strength (V/m), (iii) exposure duration, (iv) number of different exposures, (v) status of physiological effects (changed or unchanged) and (vi) year and authors.

Summary from all 45 studies of the detailed exposure conditions are shown in Tables 6 and 7. An overview of the published year and the number of publications is analyzed in Table 8 to observe the potential trend by using the data from 1996 to 2016. A pattern of effect on plants due to the RF-EMFs over the years can be observed here. Besides the lack of significant studies on each year, the results show that plants seem to be responsive to the RF-EMFs. Our analysis of the reported results suggests that substantial studies on plants indicate physiological or morphological changes due to weak radiofrequency radiation in 52 studies (89.9%) and 17 studies (10.1%) show no such changes ( $p < 0.0001$ ). Studies on plants that indicate physiological or morphological changes due to weak radiofrequency radiation, based on the publication year, can be observed from Figure 1 and Table 8. This observation should be further analyzed with more studies in the future.

Table 9 presents physiological or morphological effects on plants responses (changed or unchanged) based on the exposure duration. We analyzed the data based on various subgroups of the exposure duration. A substantial amount of studies indicate plants have experienced physiological or morphological changes due to radiofrequency radiation and show statistically significant changes for the short-term exposure duration: (i) less than 2 hours (92%,  $p < 0.001$ ), (ii) between 2 and 24 hours (98%,  $p < 0.001$ ), (iii) between 1 and 7 days (92%,  $p < 0.001$ ) and (iv) between 1 and 13 weeks (100%,  $p < 0.001$ ). In contrast, the results obtained from the



**Table 6.** Weak radiofrequency radiation exposure from mobile phones on plants: exposure conditions used in our study—data from the 45 peer-reviewed scientific articles published in 1996–2016.

No.	Frequency	SAR, power flux density power/electric field strength	Exposure duration	Number of exposures	Physiological effects		Authors
					Changed	Unchanged	
01	915 MHz (GSM)	0.4, 1, 1.6 W/kg, 23, 35.2, 46 W/m <sup>2</sup> 0.00072, 1.15 W/kg, electric field strength 5, 200 V/m	72 hours 90 minutes	3	3	0	2016 Gustavino et al. (2016)
02	900 MHz (GSM, PW, CW)	0.48 μW/kg, 0.049, 0.39, 2.6, 20 mW/kg, 0.1, 11, 86, 560, 4400 mW/m <sup>2</sup> , 10 hours 0.56, 5.7, 41 V/m	30 minutes, 1, 2 and 4 hours	5	2	0	2016 Gremiaux et al. (2016)
03	900 MHz (GSM)	1.69 W/kg, 332 mW/m <sup>2</sup> , 0.1 W	30 minutes, 1, 2 and 4 hours	4	4	0	2015 Halgamuge et al. (2015)
04	1800 MHz (CW)		10 days 1–8 hours 30 days	4	4	0	2015 Kumar et al. (2015)
05	900, 1800 MHz (GSM)	70–100 μW/m <sup>2</sup> , 0.162 V/m	10 days 1–8 hours 30 days	4	4	0	2015 Cammaerts et al. (2015)
06	1000 MHz	0.47 W/kg	0.5, 1, 2, 4, 8 hours	2	2	0	2015 Racuci et al. (2015)
07	900 MHz (GSM)	0.8–1.12 V/m	60 minutes	12	12	0	2015 Olwajobi et al. (2015)
08	900, 1800 MHz (GSM)	—	0.5, 1, 2, 4, 8 hours	20	20	0	2014 Sharma and Parihar (2014)
09	2000 MHz	0.65 μW/m <sup>2</sup>	60 minutes	1	1	0	2014a Senavirathna et al. (2014a)
10	2000, 2500, 3500, 5500, 8000 MHz (CW)	5.3, 6.6, 6.5, 6.5, 5.4 W/m <sup>2</sup> , 45, 50, 55, 60 V/m	0.5, 1 and 24 hours	15	15	0	2014b Senavirathna et al. (2014b)
11	2000, 2500, 3500, 5500 MHz (CW)	23, 25, 30 V/m	60 minutes	4	2	2	2014c Senavirathna and Asaeda (2014)
12	1250 MHz	6 V/m	10 days	1	1	0	2014 Rammal et al. (2014)
13	1800 MHz (GSM)	0.48–1.45 mW/cm <sup>2</sup> , SAR 1.0–7.1 mW/Kg	4, 24 hours	10	10	2	2014 Chan and Chen (2014)
14	860–910 MHz (GSM)	100 mW/m <sup>2</sup>	3 weeks	3	3	0	2014 Soran et al. (2014)
15	890–915 MHz	1.4 W/kg, 4.79 μW/m <sup>2</sup> , 0.00005 W/m <sup>2</sup>	3, 9 hours	2	2	0	2013 Pesnya and Romanovsky (2013)
16	2450 MHz (2280–2490 MHz)	1.58 mW	1, 4, 7, 10 hours	4	4	0	2013 Talei et al. (2013)
17	freq MHz (GSM)	970 μW/m <sup>2</sup> , 0.6 V/m	6 years	1	1	0	2013 Waldmann-Selsam and Eger (2013)
18	900 MHz (GSM, PW – talk and listen mode)	8.54 μW/cm <sup>2</sup> , 5.7 V/m	0.5, 1, 2 hours	3	3	0	2012 Singh et al. (2012)
19	1800 MHz (GSM)	1 mW, 0.76 W/kg	48 hrs 72 hours	2	2	0	2012 Akbal et al. (2012a)
20	900 MHz	—	24 hours	2	2	0	2012 Akbal et al. (2012b)
21	1287 MHz (GSM)	1.8, 7.8 V/m, 0.007, 0.16 W/m <sup>2</sup>	0.5, 1, 2, 4 hours	2	2	0	2011 Monselise et al. (2011)
22	900 MHz (GSM)	8.55 μW/cm <sup>2</sup>	1, 12, 14 hours	4	4	0	2010 Sharma et al. (2010)
23	947.5 MHz (GSM, PW, CW)	4.8 W/m <sup>2</sup> , 42.6 V/m	8 weeks	3	2	1	2010 Kouzmanova et al. (2010)
24	1000–3000 MHz	117dBm to 87dBm, 1.99e–15 to 1.99e–12 W	60 minutes	1	1	0	2010 Haggerty (2010)
25	902 MHz (GSM, PW)	4.8 W/m <sup>2</sup> , 2W		1	1	0	2009 Kouzmanova et al. (2009)

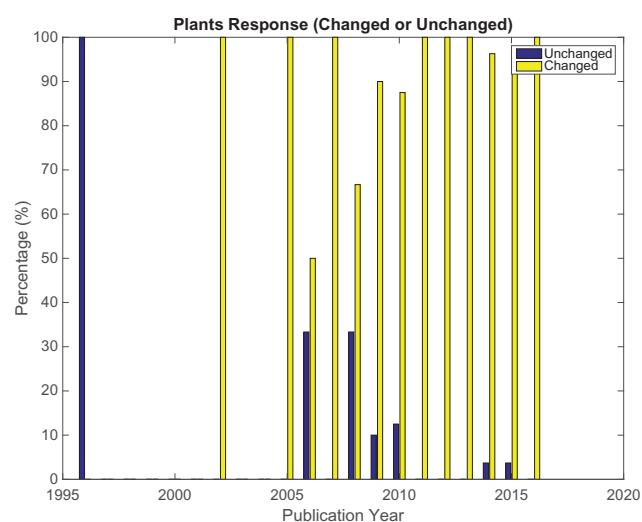


**Table 7.** Weak radiofrequency radiation exposure from mobile phones on plants: exposure conditions used in our study – data from the 45 peer-reviewed scientific articles published in 1996–2016.

No.	Frequency	SAR, power flux density/power/electric field strength	Exposure duration	Number of exposures	Physiological effects		Year	Authors
					Changed	Unchanged		
26	900 MHz (GSM, PW)	8.55 µW/cm <sup>2</sup> , 5.7 V/m SAR	0.5, 1, 2, 4 hours 1, 2, 4 hours 5–25 second	4	3	1	2009a	Sharma et al. (2009a)
27	900 MHz (GSM)	126 mW/mm <sup>2</sup>	2	3	3	0	2009b	Sharma et al. (2009b)
28	2450 MHz	0.3, 1.4, 4.2 and 38.2 W/m <sup>2</sup> , 10, 23, 41 and 120 V/m	2, 4 hours 60 minutes	6	6	0	2009	Chen et al. (2009)
29	900 MHz (GSM)	3.9 W/m <sup>2</sup>	2, 4 hours	1	0	1	2009	Tkalec et al. (2009)
30	902 MHz (GSM)	0.7–1.5 W/m <sup>2</sup>	60 minutes	1	0	1	2009	Dragolova et al. (2009)
31	935.2–960.2 MHz (GSM)	0.75 W/kg, 8 mW/cm <sup>2</sup> , 174 V/m	2 weeks	3	3	0	2009	Khalafallah et al. (2009)
32	1900 MHz	0.066 W/m <sup>2</sup> , 5 V/m	24 hours	1	0	1	2008	Engelmann et al. (2008)
33	900 MHz	0.066 W/m <sup>2</sup> , 5 V/m	10 minutes	1	1	0	2008a	Roux et al. (2008a)
34	900 MHz	0.066 W/m <sup>2</sup> , 5 V/m	10 minutes	1	1	0	2008b	Roux et al. (2008b)
35	900 MHz (CW)	0.066 W/m <sup>2</sup> , 5 V/m	10 minutes	1	1	0	2007	Beaubois et al. et al. (2007)
36	900 MHz (GSM)	0.95 mW/kg, 0.05 W/m <sup>2</sup>	0.5, 1, 2, 4, 8, 12, 24, 36 hours	8	8	0	2007	Racuci and Miclaus (2007)
37	900 MHz (CW)	0.3, 1.4, 4.2, 38.2 W/m <sup>2</sup> , 10, 23, 41, 120 V/m	2, 4 hours	6	6	0	2007	Tkalec et al. (2007)
38	900 MHz (CW)	0.066 W/m <sup>2</sup> , 5 V/m	10 minutes	1	1	0	2007	Roux et al. (2007)
39	900 MHz (UMTS, CDMA)	0.06 mW/cm <sup>2</sup> , 3.9 V/m	10 minutes	1	1	0	2006	Vian et al. (2006)
40	900 MHz (GSM, CW)	0.0066 mW/cm <sup>2</sup> , 5 V/m	2, 10 minutes	2	2	0	2006	Roux et al. (2006)
41	2400, 5850 MHz	5, 12 W/m <sup>2</sup>	7 weeks	2	0	2	2006	Skiles (2006)
42	2450 MHz	1.26 mW/mm <sup>2</sup>	8 seconds	1	1	0	2005	Chen et al. (2005)
43	900, 1900 MHz (CW, AM)	0.26, 1.4, 4.45 W/m <sup>2</sup> , 10, 23, 41 V/m	2, 4 and 14 hours	5	5	0	2005	Tkalec et al. (2005)
44	900 MHz (GSM, PW)	1 mW/cm <sup>2</sup> , 2W	2 hours	1	1	0	2002	Tafforeau et al. (2002)
45	2450 MHz	0.1–0.3 mW/cm <sup>2</sup> , 1–3 mW/cm <sup>2</sup> , 10–30 mW/cm <sup>2</sup> , < 0.0001 mW/cm <sup>2</sup>	3.5 years	8	0	8	1996	Schmitz et al. (1996)

**Table 8.** Overview of the published year: physiological or morphological effects on plants responses (changed or unchanged) due to weak radiofrequency radiation exposure from mobile phones—pooling the data from the 45 peer-reviewed scientific articles published in 1996–2016.

Published year	Number of publications	Number of exposures	Physiological effects		<i>p</i> -Value
			Changed	Unchanged	
2016	2	5	5 (100%)	0 (0%)	0.0312
2015	5	27	26 (96.3%)	1 (3.7%)	<0.0001
2014	7	54	52 (96.3%)	2 (3.7%)	<0.0001
2013	3	7	7 (100%)	0 (0%)	0.0078
2012	3	7	7 (100%)	0 (0%)	0.0078
2011	1	1	1 (100%)	0 (0%)	0.5000
2010	3	8	7 (87.5%)	1 (12.5%)	0.0313
2009	7	20	18 (90%)	2 (10%)	<0.0001
2008	3	3	2 (66.7%)	1 (33.3%)	0.375
2007	4	16	16 (100%)	0 (0%)	<0.0001
2006	3	5	3 (60%)	2 (40%)	0.3750
2005	2	6	6 (100%)	0 (0%)	0.0156
2002	1	1	1 (100%)	0 (0%)	0.5000
1996	1	8	0 (0%)	8 (100%)	0.0039
Total	45	169	152 (89.9%)	17 (10.1%)	<0.0001



**Figure 1.** Overview of the published year: physiological or morphological effects on plants responses (changed or unchanged) due to weak radiofrequency radiation exposure from mobile phones—pooling the data from the 45 peer-reviewed scientific articles published in 1996–2016.

long-term exposure studies (two publications using nine different exposures with exposure duration between 3 months to 6 years) support no physiological effects on plants when exposed to radiofrequency radiation (88.9%, *p* = 0.0176). Nonetheless, the cumulative effects

(a series of repeated exposure) are not considered in standards of exposure limits in non-ionizing radiation, as it deems only acute effects (Halgamuge, 2013).

We also examine the effects of different carrier frequency and the modulation formats (Table 10). This variation was observed by grouping the experimental data, based on the frequencies used in each experiment in 169 experimental observations. This shows effects on plants responses (changed or unchanged) based on different frequency bands. The RF-EMFs with certain frequencies, especially the frequencies between: (i)  $800 < f \leq 1500$  MHz which show 94.1% (changed) and 5.9% (unchanged) (*p* < 0.0001), (ii)  $1500 < f \leq 2400$  MHz which show 94.6% (changed) and 5.4% (unchanged) (*p* < 0.0001), and (iii)  $3500 < f \leq 8000$  MHz which show 83.3% (changed) and 16.7% (unchanged) (*p* = 0.016), seem to be more responsive to plants. Moreover, Table 11 clearly shows that certain plants, especially, maize, roselle, pea, fenugreek, duckweeds, tomato, onions and mungbean plants are more sensitive to the RF-EMFs from a mobile phone.

Figure 2 shows the comparison of all parameters: (i) published year, (ii) type of plant (iii) frequency, (iv) SAR, (v) power flux density, (vi) electric field strength, (vii) exposure time and (viii) response (unchanged or changed). Figure 3 shows the values of power flux density ( $\text{W/m}^2$ ) for different frequencies. The results

**Table 9.** Different exposure duration: physiological or morphological effects on plants responses (changed or unchanged) due to weak radiofrequency radiation exposure from mobile phones—pooling the data from the 45 peer-reviewed scientific articles published in 1996–2016.

Exposure duration	Number of experiments	Physiological effects		<i>p</i> -Value
		Changed	Unchanged	
0 < hour $\leq$ 2	75	69 (92%)	6 (8%)	<0.0001
2 < hour $\leq$ 24	50	49 (98%)	1 (2%)	<0.0001
1 < day $\leq$ 7	9	9 (100%)	0 (0%)	0.0020
1 < week $\leq$ 13	26	24 (92.3%)	2 (7.7%)	<0.0001
0.25 < year $\leq$ 6	9	1 (11.1%)	8 (88.9%)	0.0176
Total	169	152 (89.9%)	17 (10.1%)	<0.0001

**Table 10.** Different frequency levels: Physiological or morphological effects on plants responses (changed or unchanged) due to weak radiofrequency radiation exposure from mobile phones—pooling the data from the 45 peer-reviewed scientific articles published in 1996–2016.

Frequency ( $f$ ) (MHz)	Number of experiments	Physiological effects		$p$ -Value
		Changed	Unchanged	
800 $\leq f \leq$ 1500	101	95 (94.1%)	6 (5.9%)	<0.0001
1500 $\leq f \leq$ 2400	37	35 (94.6%)	2 (5.4%)	<0.0001
2400 $\leq f \leq$ 2500	15	7 (46.6%)	8 (53.3%)	0.1964
2500 $\leq f \leq$ 3500	4	3 (75.0%)	1 (25.5%)	0.2500
3500 $\leq f \leq$ 8000	12	10 (83.3%)	2 (16.7%)	0.0161
Total	169	152 (89.9%)	17 (10.1%)	<0.0001

**Table 11.** Different plants: physiological or morphological effects on plants responses (changed or unchanged) due to weak radiofrequency radiation exposure from mobile phones—pooling the data from the 45 peer-reviewed scientific articles published in 1996–2016.

Plant	Scientific name	Number of experiments	Physiological effects		$p$ -Value
			Changed	Unchanged	
Broad bean	<i>Vicia faba L.</i>	3	3 (100%)	0 (0%)	0.1250
Ligneous	<i>Rosa hybrida</i>	2	2 (100%)	0 (0%)	0.2500
Soybean	<i>Glycine max</i>	7	6 (85.7%)	1 (14.3%)	0.0547
Maize	<i>Zea mays L.</i>	17	17 (100%)	0 (0%)	<0.0001
Brassicaceae	( <i>Arabidopsis thaliana</i> )	5	4 (80%)	1 (20%)	0.1562
Roselle	<i>Hibiscus sabdariffa</i>	12	12 (100%)	0 (0%)	<0.0001
Pea	<i>Pisum sativum L.</i>	13	12 (92.3%)	1 (7.7%)	0.0016
Fenugreek	<i>Trigonella foenumgraecum</i>	10	10 (100%)	0 (0%)	<0.0001
Parrot feather	<i>Myriophyllum aquaticum Verdc.</i>	5	3 (60%)	2 (40%)	0.3125
Duckweeds	<i>Lemna minor</i>	28	28 (100%)	0 (0%)	<0.0001
Tomato	( <i>Lycopersicon esculentum</i> , VFN-8)	9	9 (100%)	0 (0%)	0.0020
Red bean	<i>Vigna, Faboideae</i>	2	2 (100%)	0 (0%)	0.2500
Hyacinth bean	<i>Lablab, Fabaceae</i>	2	2 (100%)	0 (0%)	0.2500
Mologabeen	<i>Vigna, Papilionaceae</i>	2	2 (100%)	0 (0%)	0.2500
Parsley	<i>Petroselinum crispum</i>	1	1 (100%)	0 (0%)	0.5000
Dill	<i>Anethum graveolens</i>	1	1 (100%)	0 (0%)	0.5000
Celery	<i>Apium graveolens</i>	1	1 (100%)	0 (0%)	0.5000
Onions	<i>Allium cepa – bulbs</i>	8	8 (100%)	0 (0%)	0.0039
Rice plant	<i>Oryza sativa L.</i>	4	4 (100%)	0 (0%)	0.0625
Mung bean	<i>Vigna radiata</i>	17	16 (94.12%)	1 (5.88%)	<0.0001
Lentil	<i>Lens culinaris</i>	2	2 (100%)	0 (0%)	0.2500
Common wheat	<i>Triticum aestivum</i>	4	3 (75%)	1 (25%)	0.2500
Aspen	<i>Populus</i>	1	1 (100%)	0 (0%)	0.5000
Alfalfa	<i>Medicago sativa</i>	2	0 (0%)	2 (100%)	0.2500
Plectranthus	<i>Lamiaceae</i>	1	1 (100%)	0 (0%)	0.5000
Woad	<i>Isatis indigotica</i>	1	1 (100%)	0 (0%)	0.5000
Flax	<i>Linum usitatissimum L. var Ariane</i>	1	1 (100%)	0 (0%)	0.5000
Spruce	<i>Picea abies L.</i>	4	0 (0%)	4 (100%)	0.0625
Beech	<i>Fagus sylvatica L.</i>	4	0 (0%)	4 (100%)	0.0625
Total		169	152 (89.9%)	17 (10.1%)	<0.0001

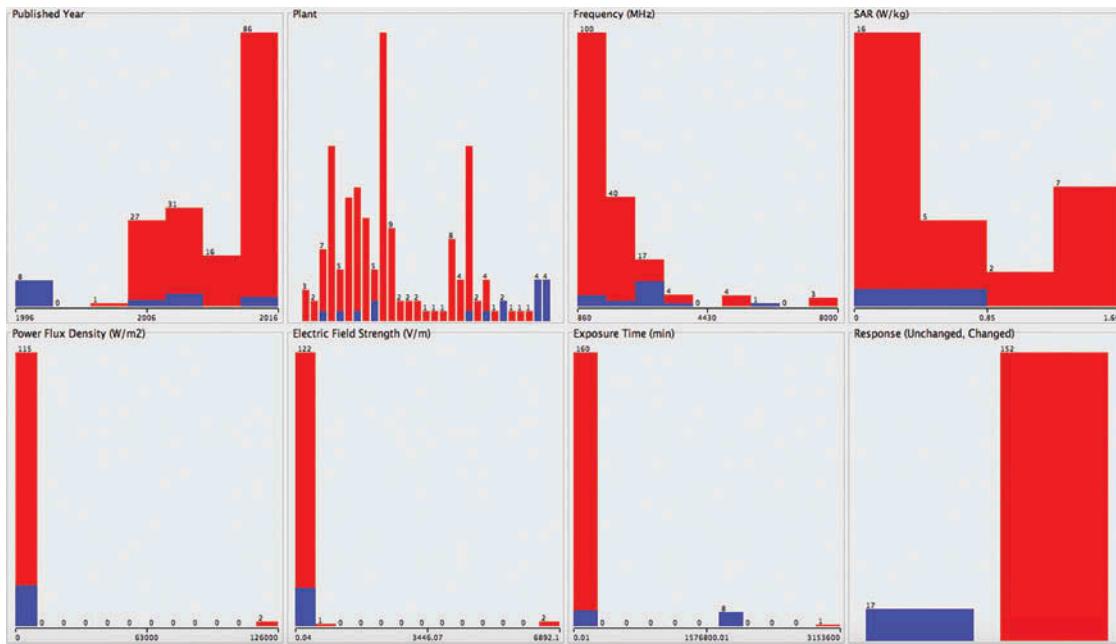
indicate that this comparison does not seem to be consistent as some studies showed that the physiological or morphological effects on plants could be changed with the lower power flux density values. Please note that due to identical exposure conditions there were overlaps of the data points in Figures 3–5. Moreover, Figure 4 shows the electric field strength values (V/m) at different frequencies. Similar to the power flux density values ( $\text{W/m}^2$ ), the comparison does not seem to be stable with the electric field strength values. Figure 5 shows the exposure duration values at different frequencies.

## Discussion

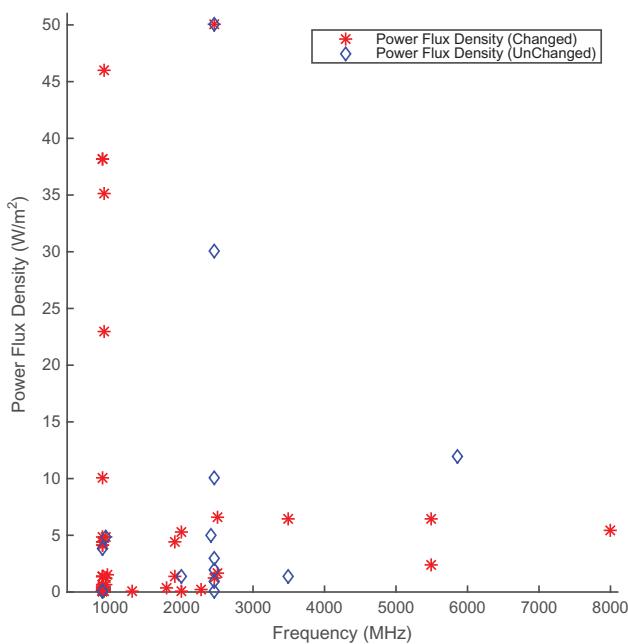
Changes in plant growth or other physiological or morphological effects on plants (changed or

unchanged) due to weak radiofrequency radiation exposure from mobile phones were observed. Our analysis from the reported studies demonstrated the potential impact of weak radiofrequency exposure from mobile phone radiation on plants. This observation was also supported by other studies (Cucurachi et al., 2016; Panagopoulos et al., 2016; Senavirathna and Takashi, 2014); however, in contrast, Verschaeve (2014) study was not supported. Irrespective to this, Panagopoulos et al. (2016) criticized Verschaeve (2014) review study about his analysis.

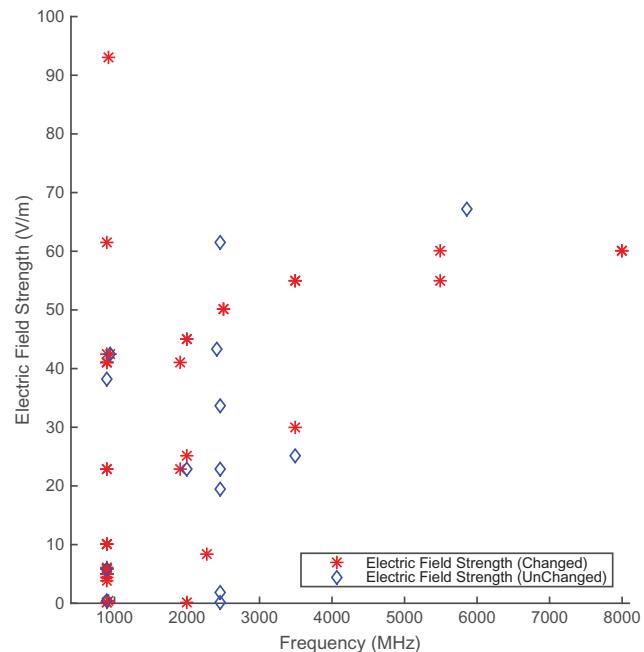
The biological effects of RF-EMF radiation from mobile communication might vary on the mean power level, frequency and modulation of the electromagnetic signal. Numerous studies questioned issues about the safety of the extended use of mobile phones; however, the most of these findings are obtained from



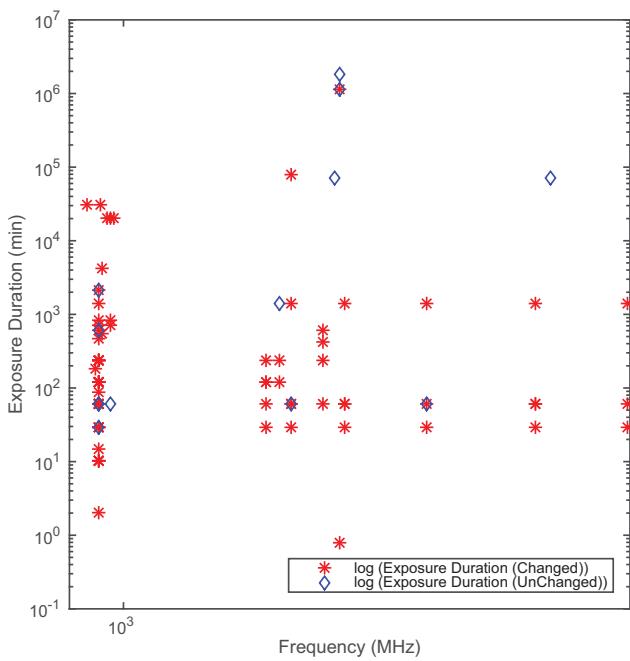
**Figure 2.** Comparison of all parameters: (i) published year, (ii) type of plant (broad bean, ligneous, soybean, maize, Brassicaceae, roselle, pea, fenugreek, parrot feather, duckweeds, tomato, red bean, hyacinth bean, mologabean, parsley, dill, celery, onions, rice plant, mung bean, lentil, common wheat, aspen, alfalfa, Plectranthus, woad, flax, spruce, beech), (iii) frequency (MHz), (iv) SAR (W/kg), (v) power flux density ( $\text{W}/\text{m}^2$ ), (vi) electric field strength (V/m), (vii) exposure time (minutes) and (viii) response (unchanged or changed): Plants exposed to RF radiation experiments that reported results (physiological or morphological effects changed or unchanged) for different frequency using the data from the 45 studies (169 different exposures). Please note that unchanged areas are in blue color and changed areas are in red color.



**Figure 3.** Comparison of the power flux density values for different frequencies: plants exposed to RF radiation experiments that reported results (physiological or morphological effects changed or unchanged) for different frequency using data from the 45 studies (169 different exposures). Please note that due to identical exposure conditions there were overlaps of data points.



**Figure 4.** Comparison of the electric field strength values for different frequencies: plants exposed to RF radiation experiments that reported results (physiological or morphological effects changed or unchanged) for different frequency data from the 45 studies (169 different exposures). Please note that due to identical exposure conditions there were overlaps of data points.



**Figure 5.** Comparison of the exposure duration time values for different frequencies: plants exposed to RF radiation experiments that reported results (physiological or morphological effects changed or unchanged) for different frequency data from the 45 studies (169 different exposures). Please note that due to the identical exposure conditions there were overlaps of the data points.

epidemiological, animal (*in vivo*) or cell (*in vitro*) studies. Only a few studies investigated the effects of RF-EMF radiation on plants. The RF-EMF radiation is identified to have a biological effect on living organisms, and research over the many years has shown that the biological processes in living organisms are more responsive to low-intensity radiation (Bolen, 1988). Investigations in the field of effects of the weak RF-EMFs and radiation have focused on animals (Eberhardt et al., 2008; Finnie et al., 2009; Gannes et al., 2009; Hirota et al., 2009; Masuda et al., 2009; Nittby et al., 2011; Tang et al., 2015), plants (Gremiaux et al., 2016; Gustavino et al., 2016; Halgamuge et al., 2015; Kumar et al., 2015; Senavirathna et al., 2014a, b), epidemiological evidence (Benson et al., 2013; Hardell et al., 2005, 2009; Johansen et al., 2001; Linet et al., 2006; Schüz et al., 2006), children (Elliott et al., 2010; Li et al., 2012; Sudan et al., 2013a, b), human sleep research (Arnetz et al., 2007; Danker-Hopfe et al., 2010, 2015; Leitgeb et al., 2008; Loughran et al., 2012; Lowden et al., 2011; Regel et al., 2007) and cell cultures (Hook et al., 2004; Kazemi et al., 2015; Kim et al., 2015; Koyama et al., 2015; Liu et al., 2015).

Many types of research used 900 MHz (Cucurachi et al., 2016; Senavirathna and Takashi, 2014) as 900

MHz frequencies are utilized in GSM technology. EMR frequencies between 2000 and 6000 MHz are being tested due to the expansion of UMTS technology for mobile phone communication (Senavirathna and Takashi, 2014). Besides, a study by Radic et al. (2007) found some effects on *Lemna minor*, 900 MHz, 2–4 hours, signal strength 10–120 V/m.

The frequency 156–162 MHz and intensity of 0.1–2.6  $\mu\text{W}/\text{cm}^2$ , on duckweed (*Spirodela polyrhiza*) (Magone, 1996), found a significant effect. Old studies (1996) that used very lower band microwaves (frequency between 154 and 162 MHz) found the important effects on plants: (i) pine (*Pinus sylvestris*) (Balodis et al., 1996), (ii) great duckweed (*Spirodela polyrhiza* Schleiden), 156–162 MHz, 0.0018  $\text{mW}/\text{cm}^2$  (Magone, 1996) and (iii) pine (*Pinus sylvestris*), 154–162 MHz, 16.57  $\text{mW}/\text{cm}^2$  (Selga and Selga, 1996).

A few studies used on lower band microwaves (frequency frequency between 380 and 425 MHz) found the significant effects on plants: (i) mung bean plant (*Vigna Radiate L.*), 425 MHz, 0.1, 0.001  $\text{W}/\text{m}^2$  (Jinapang et al., 2010), (ii) maize plant (*Zea maize*), 418 MHz, 6  $\text{W}/\text{m}^2$  (Ursache et al., 2007), (iii) duckweed plant (*Lemna minor*), 400 MHz, 0.26  $\text{W}/\text{m}^2$  (Tkalec et al., 2005), (iv) black locust plant (*Robinia pseudoacacia L.*), 400 MHz 2  $\text{W}/\text{m}^2$  (Sandu et al., 2005) and (v) pine (*Conifer needles plant*), *Pinus pumila*, *Abies alba*, *Abies grandis*, 383 MHz (Lerchl et al., 1999), except one study on onion plant (*Allium cepa plant*), 400 MHz, 1.4 or 4.5  $\text{W}/\text{m}^2$  (Tkalec et al., 2009).

More studies interrogated the effects from GHz frequencies besides the effect from weak RF-EMF on plants and found significant effects: (i) Tanner and Romero-Sierra (1974) on *Mimosa* plant, 10 GHz, 190  $\text{mW}/\text{cm}^2$ , 5–10 minute exposure, (ii) Scialabba and Tamburello (2002) on radish (*Raphanus sativus*) plant, 10.5 GHz, 14 mW, (iii) Tafforeau et al. (2004) on *Linum usitatissimum*, 105 GHz for 2 hours, (iv) Ragha et al. (2011) on *Vigna radiata*, *Vigna aconitifolia*, *Cicer arietinum* and *Triticum aestivum* plants, 9.6 GHz frequency.

Besides, a few other studies dealt with the long-term effects of radiation on plants and trees (Balmori, 2004, 2014; Waldmann-Selsam and Eger, 2013). The study by Murakami et al. (2001) with a frequency of 2.45 GHz and an intensity of between 1 and 15  $\text{mW}/\text{cm}^2$  detected a slight plant growth rate increment even at the lowest intensity. In contrast, the study by Urech et al. (1996) shows reduced growth at the same frequency (2.45 GHz) intensities of 0.2, 5.0 and 50.0  $\mu\text{W}/\text{cm}^2$  on the *Hypogymnia physodes* plants, although it was unable to

differentiate the effects of thermal and non-thermal behavior.

The effect of very low frequency (VLF) EMF (50 Hz, 15 µT) on thistle plants (*Cynara cardunculus*) and lentils (*Lens culinaris*) found (Picazo et al., 1999) significant difference decreased in both weight and length during the 3-week exposure period. In contrast, VLF EMFs (50 Hz, 100 µT) on cress seedlings (*Lepidium sativum*) found (Ruzic and Jerman, 2000) no such effect during the 40-minute exposure period. The study from Trebbi et al. (2007) using extremely low frequency (ELF) magnetic fields (10 Hz, 28.9 µT) show effects after 8- or 24-hour exposure. The study from Haider et al. (1994) using Spiderwort plants (*Tradescantia*) exposed to VLF EMFs (10–21 Hz, 0.43 mW/cm<sup>2</sup>) showed the clastogenic effect in all distances and levels of the electric field.

Several studies exposed biological matters to RF-EMF radiation at significantly high SARs of 200 W/kg (Koyama et al., 2004; Takashima et al., 2006; Wang et al., 2005, 2006), 104–200 W/kg (Lloyd et al., 1984, 1986), 100 W/kg (Cleary et al., 1997; Komatsubara et al., 2005; Koyama et al., 2003, 2004; Tian et al., 2002; Wang et al., 2005, 2006), 51.75 and 103.5 W/kg (Parker et al., 1988), 90 W/kg (d'Ambrosio et al., 1995), 75–79 W/kg (Cleary, 1995; Koyama et al., 2003; Maes et al., 1993) and 50 W/kg (Cleary, 1995; Komatsubara et al., 2005; Koyama et al., 2003, 2004; Rao et al., 2008; Tian et al., 2002; Wang et al., 2006, 2005). The reason for using these high SAR values from the experiments is to compare the potential effects with low SAR values.

The existing studies to date that investigate the effects of the long-term exposure of RF-EMFs on plants are too limited to obtain a viable conclusion on whether there is a significant effect or not. Nonetheless, our review shows that there is a substantial amount of studies which indicate that plants have experienced physiological or morphological changes due to radiofrequency radiation and show statistically significant changes for the short-term exposure duration (up to 13 weeks). In contrast, the results obtained from the long-term exposure studies (two publications using nine different exposures with exposure duration between 3 months to 6 years) support no physiological effects on plants when exposed to radiofrequency radiation from mobile phone radiation. This would bring a remarkable point to the discussion about the apparent absence of response to the long-term exposure that may be interpreted as adaptations. On the other hand, phenotypic plasticity of plants will permit them to change their structure and function; hence, plants to adapt to environmental change (Nicotra et al., 2010). Plants are naturally affected by environmental stresses due to their immobility. Plants could respond to the environmental factors of wind, rain, electric field

and ultraviolet radiation and adjust its physiological condition to adapt to the change of environment (Braam and Davis, 1990; Braam et al., 1996; Mary and Braam, 1997). Investigating this phenomenon could be an interesting avenue to explore in the future. More repetitive laboratory experiments and field studies are needed (Cucurachi et al., 2016; Halgamuge, 2013; Senavirathna and Takashi, 2014) for future studies to further observe relevant physical parameters that influence biological effects of RF-EMF. To support this, our previous findings (Halgamuge et al., 2015) indicate that the biological effects considerably relied on field strength and amplitude modulation of the applied field.

It is emphasized that our statistical test shows particularly whether there are effects (changed or unchanged) on plant responses being reported in the literature and if this difference is statistically significant. Nevertheless, this reinforces the need for more potential experiments to observe RF-EMF effects with longer exposure durations using a whole organism.

## Conclusion

In this review paper, we performed an analysis of the data obtained from the 45 peer-reviewed scientific publications (1996–2016) describing 169 experimental observations carried out in the scientific literature, which discussed the potential effects on plants exposed to the non-thermal, weak, RF-EMFs from mobile phone radiation. Our observation of the data from the reported studies showed significant effects on plants that exposed to radiofrequency radiation. Hence, this study provides new evidence supporting our hypothesis. None of these findings can be directly associated with human; however, on the other hand, this cannot be excluded, as it can impact the human welfare and health, either directly or indirectly, due to their complexity and varied effects (calcium metabolism, stress proteins, etc.). This study should be useful as a reference for researchers managing epidemiological studies and the long-term experiments, using whole organisms, to observe the effects of RF-EMFs.

## Declaration of interest

The authors declare no conflict of interest.

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## Appendix

### **List of abbreviations**

Adenosine triphosphate (ATP), code division multiple access (CDMA), continuous wave (CW), Committee on Emerging and Newly Identified Health Risks (SCENIHR), European Committee for Electrotechnical Standardization (CENELEC), European health risk assessment network (EHFRAN), fifth-generation networks (5G), first-generation networks (1G), frequency division multiple access (FDMA), frequency-modulated continuous wave (FMCW), fourth-generation networks (4G), Gaussian minimum shift keying (GMSK), global

system for mobile communications (GSM), GSM-DTX (hearing only), GSM-non DTX (speaking only), GSM-Talk (34% speaking and 66% hearing activity), high-speed downlink shared channel (HS-DSCH), high-speed downlink packet access (HSDPA), International Agency for Research on Cancer (IARC), International Commission on Non-Ionizing Radiation Protection (ICNIRP), long-term evolution (LTE), pulsed wave (PW), pulsed electromagnetic fields (PEMF), radiofrequency (RF), radiofrequency radiation (RFR), second-generation networks (2G), third-generation networks (3G), time division multiple access (TDMA), time division synchronous code division multiple access (TD-SCDMA), universal mobile telecommunications system (UMTS), Wideband code division multiple access (WCDMA), World Health Organization (WHO), world wide wireless web (WWW).